Performance of a Residential-Scale Stationary Fuel Cell System

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Introduction

In an effort to provide performance data useful in the development of rating procedures, the National Institute of Standards and Technology (NIST) has measured the performance of a 5-kW, grid-interconnected, stationary fuel cell system. NIST envisions a testing and rating methodology that predicts the annual energy production and fuel consumption of fuel cell systems. Such a rating methodology would provide consumers with a means to estimate the economic potential of implementing a fuel cell in various applications.

NIST recognized that adequate, high-quality data needed to completely characterize the performance of fuel cell systems did not exist, and created a test facility to determine the important parameters affecting the performance of residential-scale systems. The test facility measures the electrical and, if available, thermal output of the fuel cell system, the energy content of the fuel supplied to the system, and the surrounding ambient conditions. These measurements are performed while the facility controls the ambient temperature, relative humidity, electrical load and thermal load. This paper will discuss the thermal and electrical performance of a fuel cell system at steady-state conditions.

Test Facility Description

The test facility measures the electrical and thermal performance of fuel cell systems and controls the primary variables affecting its performance [1,2]. The primary measurements and controlled parameters are shown in Table 1 along with the expanded uncertainties of the measurements.

Table 1 . Primary measured parameters and uncertainties

Measurement	Control?	Expanded Uncertainty (k=2)
Electrical Power Output (kW)	Yes	0.7 %
Thermal Power Output (kW)		4.0 %
- Heat Transfer Fluid Inlet Temperature (°C)	Yes	0.1 %
- Heat Transfer Fluid Flow Rate (LPM)	Yes	1.2 %
Fuel Power Input (kW)		0.6 %
- Fuel Volume Consumed (L)		0.2 %
- Fuel Energy Content, HHV (J)		0.55 %
Ambient Temperature (°C)	Yes	0.3 °C
Ambient Relative Humidity (%)	Yes	2.5 %
Electrical Efficiency (%) [i.e. 18 % ± 0.25%]		0.25 %
Thermal Efficiency (%) [i.e. 40 % ± 2.0%]		2.0 %

Individual tests were considered to be two-hour periods with a steady electrical output, thermal output, and ambient conditions. For each test, the electrical and thermal efficiencies were calculated. Total system efficiency is the sum of the electrical and thermal efficiency for each test.

$$\eta_{electrical} = \frac{\sum E_{elec}}{\sum V_{fuel} \cdot E_{fuel}} \qquad \eta_{thermal} = \frac{\sum \rho \cdot c_p \cdot V_{fluid}(T_{outlet} - T_{inlet})}{\sum V_{fuel} \cdot E_{fuel}}$$

Where
E_{elec} = Electrical energy output, J

V_{fuel} = volume of fuel consumed during time step, m³

E_{fuel} = energy content of fuel (higher heating value), J/m³

$$\rho \;=\quad \text{density of heat transfer fluid, kg/m}^3$$

$$c_p \;=\quad \text{specific heat of heat transfer fluid, kJ/kg/K}$$

$$V_{fluid} =\quad \text{volume of fluid that passed through fuel cell during time step, m}^3$$

$$T_{outlet} =\quad \text{temperature of heat transfer fluid at outlet of fuel cell system, C}$$

$$T_{inlet} =\quad \text{temperature of heat transfer fluid at inlet of fuel cell system, C}$$

Test Method

The test facility was used to subject a fuel cell system to steady-state electrical and thermal loads at different levels of the five controlled parameters: electrical load, thermal load, ambient temperature, and ambient relative humidity. The thermal load was varied by selecting a flow rate and supply temperature. Two levels were designated for each parameter, except relative humidity. Relative humidities were classified as high or low at the two ambient temperatures chosen, but because of physical limitations, the same two relative humidity levels could not be attained at the two ambient temperatures. Table 2 shows the levels for each parameter.

Table 2. High and Low Levels of Control Parameters

Parameter	High Level	Low Level
Electrical load fraction (% of max output)	100%	50%
Fluid flow rate	35 LPM	5 LPM
Fluid Inlet Temperature	55°C	18°C
Ambient Temperature	35°C	11.5°C
Relative Humidity @ Tamb=35°C	75%	40%
Relative Humidity @ Tamb=11.5°C	55%	25%

While a fully-randomized n-1 factorial test plan was originally designed to efficiently determine each parameters effects on the system's performance, several weeks of testing showed a noticeable degradation in the electrical efficiency of the system. The original test plan included periodic tests at the same conditions to quantify the expected degradation, but the drop in electrical efficiency between these periodic tests was of greater magnitude than the changes in performance due to the changing test parameters. Therefore, a bracketing test scheme was developed to ensure differentiation between performance degradation effects and parameter change effects. The level of a single parameter changed between the first and second tests in a three-test bracket, and the third test repeated the first to quantify any degradation that occurred over the three tests. Brackets were setup with respect to the fluid flow rate and fluid temperature (Table 3), which minimized the time between tests and the amount of degradation. This set of 10 tests was repeated at the 8 different combinations of electrical load level and ambient conditions. Unfortunately, not every three-test bracket could be completed satisfactorily. At an electrical load fraction of 50%, ambient temperature of 11.5 °C, fluid inlet temperature of 55 °C, and a fluid flow rate of 5 LPM, the fuel cell system could not output a steady electrical current, which was caused by control algorithms

Table 3. Thermal Fluid Flow Rate and Inlet Temperature for Test Sequence

Test Number	Fluid Flow Rate (LPM)	Fluid Inlet Temperature (°C)
1	35	55
2	5	55
3	35	55
4	35	18
5	35	55
6	5	18
7	35	18
8	5	18
9	5	55
10	5	18

internal to the fuel cell system. The manufacturer attempted to remedy the issue, but no solution could be found. Therefore, the four brackets that included a test at these conditions will not be considered in this discussion.

Fuel Cell System Description
A Plug Power Gensys 5c[*] fuel cell system was purchased for the purpose of developing performance testing methods as mentioned above. The system uses a PEM fuel cell to convert natural gas to electricity and heat. It is capable of producing 5 kW of electrical power and approximately 10 kW of thermal power. Electrical power is output at 120 VAC and 60 Hz to either the utility grid or to an auxiliary load panel for the customer. During an electrical utility outage, the fuel cell system continues to power the customer's auxiliary load panel. For thermal loads, an internal heat exchanger is used to transfer heat from the system to the customer's heat transfer fluid, which in this case is a mixture of 35% propylene glycol and 65% water.

Results
The test plan was designed to determine the effect of the five different parameters on the performance of the fuel cell system, and the electrical and thermal efficiency of the system were chosen as the principal metrics of performance. Table 4 shows the electrical and thermal efficiencies for each test performed. The electrical efficiencies range from 16.4 % to 20.7 %, and are considerably less than the typical electrical efficiency quoted for PEM fuel cells (25 % to 40 %) [3]. However, care must be taken to compare efficiencies quoted here with systems fueled by natural gas that produced AC electricity and calculations that use the higher heating value of natural gas. The thermal efficiency ranged from 10.0 % to 47.9 %. This wide range of thermal performance was largely due to the low thermal output at 5 LPM and 55 °C. At this condition, the operating temperature of the system prevents the fluid stream from absorbing the full thermal load of the fuel cell system, and the system's internal radiator is employed to dissipate the remaining heat load.

Throughout the testing, the fuel cell system showed significant variability between test repetitions. Variability resulted from short-term oscillations due to the system's internal control algorithms, long-term degradation of the system, a fuel cell stack change out, and occasional system malfunctions and the subsequent repairs. For this reason, only differences in performance due to the parameter change within a bracket (where the variability has been quantified) can be accurately compared. A relative index was created to quantify the performance change for each parameter variation. It is assumed that while the gross efficiency values may vary, the relative changes in

Table 4. Electrical and Thermal Efficiencies at Each Parameter Level Combination

Fluid Flow Rate (LPM)	Fluid Inlet Temp (°C)	Tambient = 35°C								Tambient = 11.5°C							
		RH = 40%				RH = 75%				RH = 55%				RH = 25%			
		LF = 100%		LF = 50%		LF = 100%		LF = 50%		LF = 100%		LF = 50%		LF = 100%		LF = 50%	
		El %	Th %	El %	Th %	El %	Th %	El %	Th %	El %	Th %	El %	Th %	El %	Th %	El %	Th %
35	55	18.0	39.2	20.1	37.2	16.8	36.8	20.2	35.9	18.6	36.6	19.5	28.9	18.5	36.8	19.5	29.6
5	55	18.1	10.9	20.2	21.5	16.4	10.0	20.1	21.2	18.4	11.5	b	b	19.0	11.6	b	b
35	55	18.3	39.6	20.2	37.3	16.4	36.0	20.4	36.4	18.4	36.4	19.4	28.8	18.4	37.1	c	c
35	55	a	a	a	a	19.5	39.9	a	a	a	a	a	a	a	a	a	a
35	18	18.4	42.9	20.3	42.6	19.2	45.9	20.4	43.7	18.1	42.3	19.2	34.5	18.7	41.2	c	c
35	55	18.8	39.7	20.2	36.8	17.4	37.8	20.2	36.0	18.2	36.7	19.5	27.8	18.7	37.1	c	c
5	18	18.7	44.5	20.2	44.0	18.5	45.9	20.7	46.1	17.5	43.7	19.4	35.5	18.4	41.4	19.5	36.8
35	18	18.9	43.6	20.1	42.5	18.6	47.9	20.6	44.3	17.2	44.2	19.6	34.0	18.7	40.6	19.7	35.7
5	18	19.1	44.8	20.1	44.5	18.8	46.5	20.7	45.6	17.4	42.4	19.5	35.7	18.5	41.6	19.9	37.6
5	55	19.0	11.5	19.9	21.4	17.8	10.8	20.2	22.1	17.5	10.9	b	b	18.3	11.2	b	b
5	18	18.8	44.8	20.2	45.3	17.0	45.6	20.1	45.5	17.2	44.2	19.8	37.3	18.5	41.8	19.6	38.0

a   Valid tests in this row were needed to properly bracket following tests after testing stopped mid-bracket. Therefore, other tests in row were not necessary

b   System would not output steady current due to internal control issues. Data not valid   c   These tests were not completed.

Table 5. **Relative change in electrical or thermal efficiency within three-test brackets**

Ambient Temp °C	RH %	Elec Load Fract (%)	35 LPM @ 55 °C / 5 LPM @ 55 °C		35 LPM @ 55 °C / 35 LPM @ 18 °C		5 LPM @ 18 °C / 35 LPM @ 18 °C		5 LPM @ 18 °C / 5 LPM @ 55 °C	
			Elec Eff Index	Thml Eff Index	Elec Eff Index	Thml Eff Index	Elec Eff Index	Thml Eff Index	Elec Eff Index	Thml Eff Index
35	40	100	1.00	**0.28**	0.99	**1.08**	1.00	0.98	1.00	**0.26**
		50	1.00	**0.58**	1.00	**1.15**	1.00	0.96	0.99	**0.48**
	75	100	0.99	**0.28**	a	a	1.00	1.04	a	a
		50	0.99	**0.59**	1.00	**1.21**	1.00	0.97	0.99	**0.48**
11.5	55	100	0.99	**0.31**	0.99	**1.16**	0.99	1.03	1.02	**0.25**
		50	b	b	0.99	**1.22**	1.01	0.95	b	b
	25	100	1.03	**0.31**	1.01	**1.11**	1.01	0.98	a	a
		50	b	b	c	c	1.00	0.96	b	b

a   The 1st and 3rd tests in these brackets did not fall within the bounds of uncertainty
b   System would not output steady current due to internal control issues. Data not valid
c   These tests were not completed.

performance should be reasonably constant and, therefore, could be readily compared between ambient conditions and load fraction levels. Only brackets in which the variability between the 1st and 3rd test efficiencies were within the bounds of the expanded uncertainty for both electrical and thermal performance were considered.

$$Index = \frac{(\eta_2)}{\frac{(\eta_1 + \eta_3)}{2}}$$ where η_i = electrical or thermal efficiency of test i in the three-test bracket.

An index close to unity for either the electrical or thermal efficiency indicates that the parameter change did not affect the performance. Table 5 shows the relative index for the electrical and thermal efficiency of each of the brackets, and **bolded** indices indicate parameter changes that resulted in statistically significant changes in performance.

Summary

According to the relative index for electrical efficiency, changing the thermal load does not affect the electrical performance of the fuel cell system. The thermal performance, understandably, was affected by changes in the thermal load. At a fluid temperature of 18°C, an increase in the flow rate did not result in a statistically significant performance change, but every other set of parameter changes affected the thermal performance of the system.   Because of low thermal energy availability in the brackets that included the 55 °C / 5 LPM test, both brackets that included such tests showed large differences in thermal performance. Smaller differences were seen in the brackets that changed the inlet temperature at the 35 LPM flow rate. Future publications will investigate the effects of ambient conditions, transient electrical loads, transient thermal loads, and domestic hot water loads. Additionally, future plans include the testing of similar residential-scale fuel cell systems from other manufacturers.

[1]   M.W. Davis and A.H. Fanney, "Test Facility for Determining the Seasonal Performance of Residential Fuel Cell Systems," Proceeding of the Hydrogen and Fuel Cells 2003 Conference and Trade Show, Vancouver, BC, Canada, 9-13 Jun. 2003
[2]   M.W. Davis, "Proposed Testing Methodology and Laboratory Facilities for Evaluating Residential Fuel Cell Systems," NISTIR 6848, Jan. 2002
[3]   N. Josefik, M. Binder, F. Holcomb, "Department of Defense Fuel Cell Programs," Proceedings of the 2003 Fuel Cell Seminar, Miami, FL, 3-7 Nov. 2003.